# Reflections on LHC Transverse Instabilities

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E-cloud wake and nonlinearity effects

Three-beam Instability in LHC

# Main Factors

- E-cloud influences incoherent and coherent oscillations of beam particles in various aspects.
  - It works as a static lens, shifting up all coherent and incoherent tunes.
  - It gives a significant tune spread. With the size of the e-cloud similar to the proton beam size, the nonlinear tune spread is comparable to the tune shift. The tune spread is defocusing with the amplitude.
  - As a reactive medium, e-cloud works as a sort of low-Q impedance at the electron bounce frequency $\omega_e$ which phase advance on the bunch rms length is

$$\psi_e \cong 0.4\sqrt{N_b r_e \sigma_z / \sigma_x^2}$$

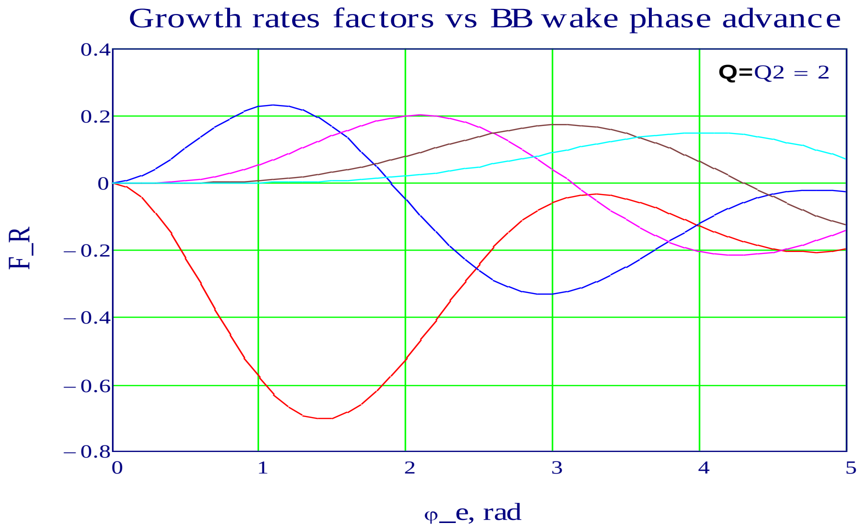
- Note that number of e-cloud pinches per p-bunch is $\sim \psi_e$ . Thus, for $\psi_e \gtrsim 1$ the effective size of the electrons within the proton beam is ~2-3 times smaller than the proton bunch radius.

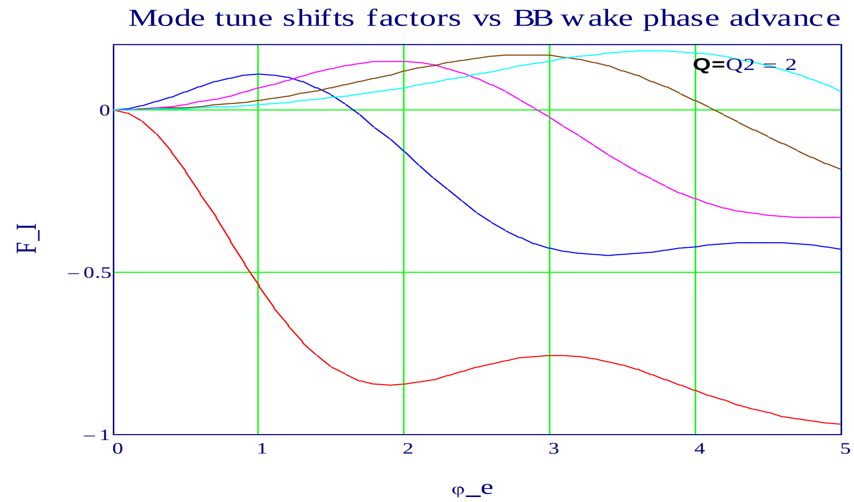
# Weak Head-Tail (WHT)

- Application this wake function to the WHT tune shift and growth rate (A. Chao, Eq. 6.213, air-bag) results in (HT phase $\chi \le 1$ ) :

$$\mathrm{Im}[\Delta Q] = \chi \Delta Q_{e0} F_R(m, \phi_e); \quad \mathrm{Re}[\Delta Q] = \Delta Q_{e0} F_I(m, \phi_e); \quad \phi_e = \sqrt{2}\omega_e \sigma_z / c$$

$$\Delta Q_{e0} = N_e r_p / (4\pi\varepsilon_n)$$




$$F_R(m, Q, \phi) = 3\int_0^\infty \frac{J_m(x\phi) J'_m(x\phi)}{1 + Q^2 (x - 1/x)^2} \frac{dx}{x}; \quad F_I(m, Q, \phi) = \frac{3}{2}\int_0^\infty \frac{Q(x - 1/x) J_m^2(\phi x)}{1 + Q^2 (x - 1/x)^2} \frac{dx}{x}$$

Unstable modes have positive tune shift – thus, they are not L-damped after the SD shift s to the left due to e-cloud unharmonicity!

At $\chi \simeq 1$ , for the MUM: $\mathrm{Im}[\Delta Q] \approx \mathrm{Re}[\Delta Q] \approx 0.2 \Delta Q_{e0}$ (used for markers at p.3 plot)

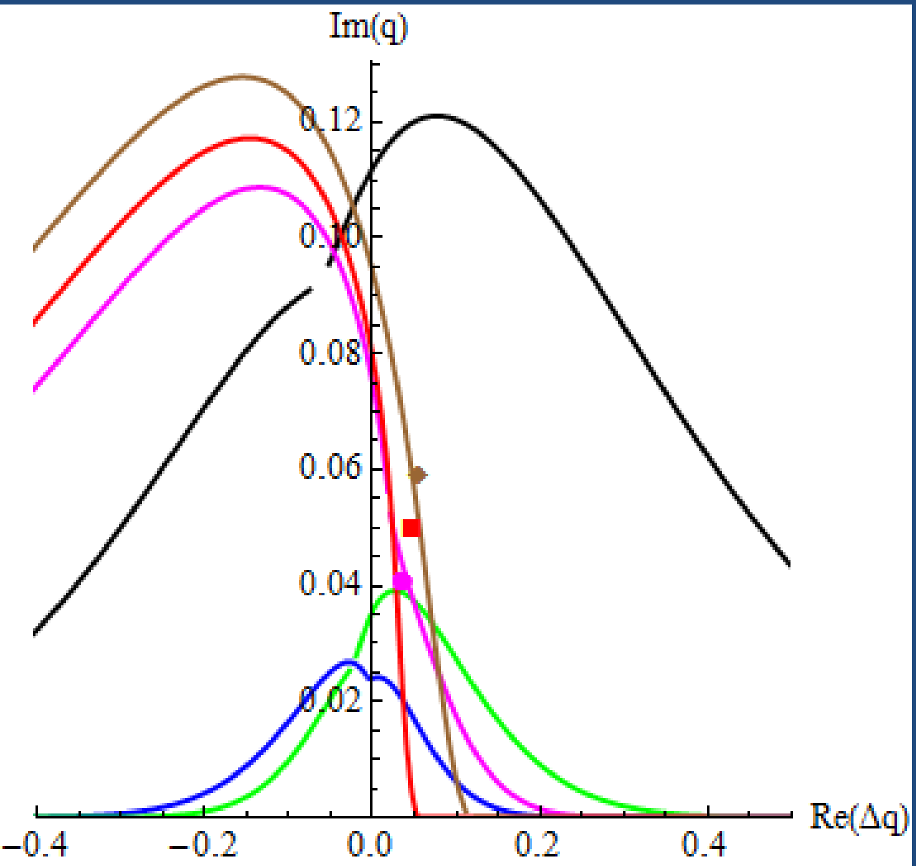
# Stability Diagrams, EoS, LO+

Assuming e-cloud transverse profile same as for the beam, the incoherent tune follows:

$$\Delta Q_e = \Delta Q_e^{(0)} + \Delta Q_e^{(1)} + \ldots$$

$$\Delta Q_e^{(0)} = \frac{N_e r_p}{4\pi\varepsilon_n}$$

$$\Delta Q_{ex}^{(1)} = -\frac{3\Delta Q_e^{(0)}}{8}\frac{J_x + 2J_y/3}{\varepsilon}; \quad \langle J_{x,y} \rangle = \varepsilon.$$




LO=200A – single beam threshold

BB only (*with Xavier correction 0.5*), LO=0

BB and LO=500A

BB, LO=500A, Ne=0.9E10

BB, LO=500A, Ne=1.1E10

BB, LO=500A, Ne=1.3E10

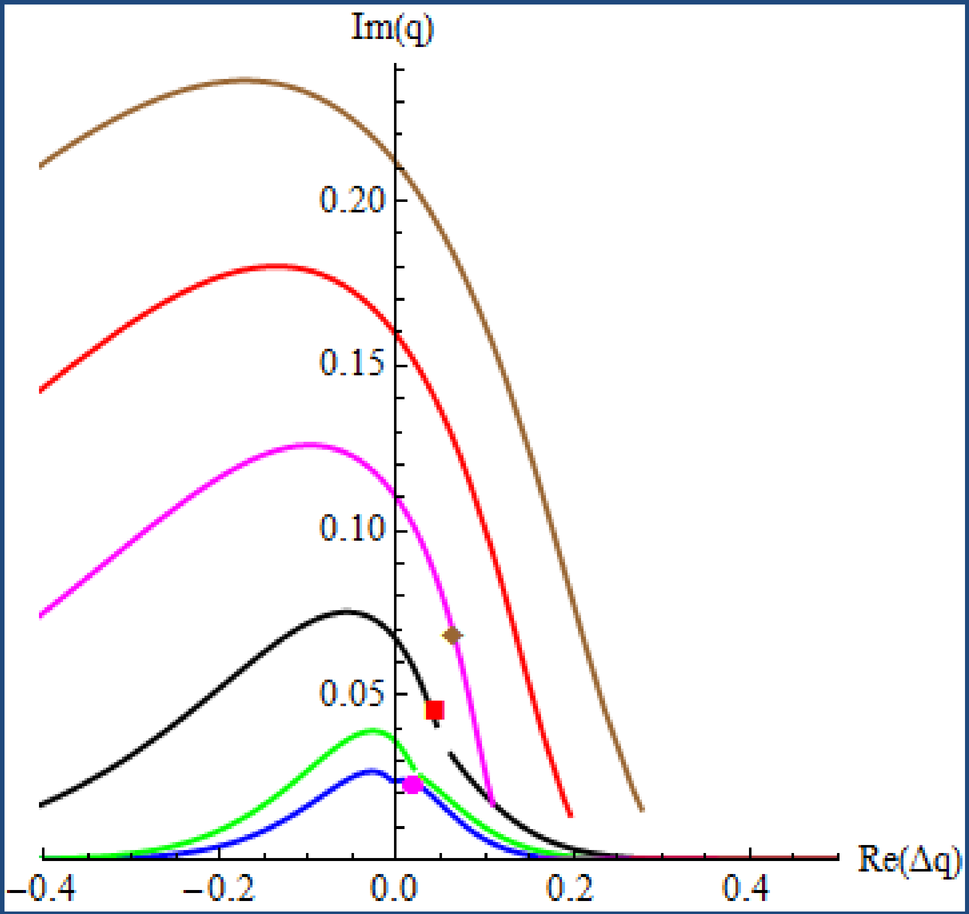
*Markers – MUMs, colors correspond*

$\Delta Q_e^{(0)} = 8 \cdot 10^{-4} \Leftrightarrow N_e = 1.3 \cdot 10^{10}$ total

$N_e \equiv 2\pi n_e \sigma_\perp^2 L$

for the single beam Similar e-cloud thresholds are.

# Stability Diagrams, EoS, LO-




**LO=-200A**

**BB only, LO=0**

**BB and LO=-500A**

**BB, LO=-500A, Ne=0.5E10**

**BB, LO=-500A, Ne=1.0E10**

**BB, LO=-500A, Ne=1.5E10**

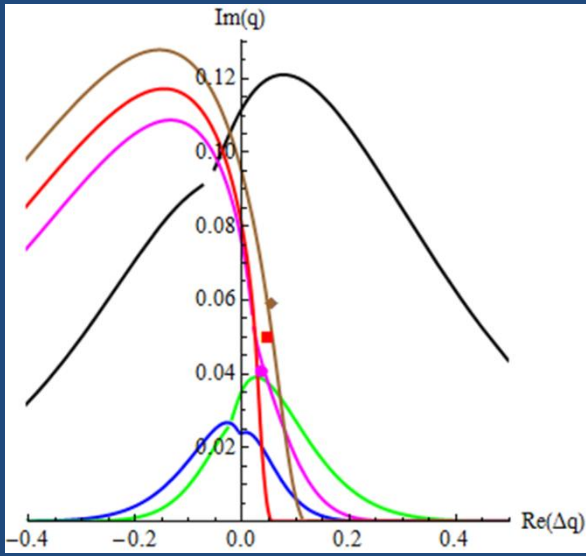
***Markers – MUMs, colors correspond***

There is no weak HT instability for this polarity, except, perhaps, at few sigmas of BB separation. Strong HT is possible, requiring ~ 10 times more electrons.

Similar e-cloud thresholds are for the single beam.

# Why End of the Squeeze?

- According to the air-bag plots of p.5, the most unstable mode (MUM) number $l \cong 1.4\psi_e$ . To be not suppressed from the longitudinal L-damping this number cannot be too high, $\psi_e \lesssim 1-2$. For the growth rate do not be too low, the electron phase advance cannot be too small as well, $\psi_e \gtrsim 1$. Thus, to drive the instability, the phase has to be about 1:




$$\psi_e \sim 1$$

- During the squeeze, the phase advance $\psi_e$ significantly changes:

$$\psi_e = \begin{cases} 9 \text{ rad} \quad \text{for } \beta = 300\text{m} \\ 2 \text{ rad} \quad \text{for } \beta = 4\text{km} \end{cases}$$

- Thus, the effective number of electrons $N_e$ has to be shared between 4 high –beta regions of IR1 and IR5, requiring ~4E9 e per every ~25m region.
- Due to the e-pinches, this number can be several times lower.

# Injection

At the injection, the e-cloud phase advance $\psi_e$ computed at the regular part of machine is about the same as in the triplet at the top energy. Thus, all the results for single beam from above apply. The threshold number of electrons for weak HT instability scales as

$$N_e \propto I_{\text{oct}} / \gamma$$

For the strong HT:

$$N_e \propto Q_s$$

# e-cloud summary

- So far, all reproducible observations are in agreement with e-cloud EoSI hypothesis or showing its potential for explanation:
  - No EoS at LO<0;
  - Sensitivity to the squeeze and other beam at IR1&IR5;
  - Possibility to explain humps (Kevin)

- LO<0 is looking more preferable for e-cloud instability. In case adjust is fast enough, an order of magnitude higher Ne threshold at the squeeze may allow to avoid the instability.

- To confirm or exclude 3-beam instability hypothesis, a comparative MD study could be provided for EoS case, measuring the LO thresholds of 1X1 and, say, 36X36 bunches.

# Poor Reproducibility

With the damper on, all the instabilities dynamically are single-bunch, unless high-frequency high-Q HOM case, which seems to be excluded for LHC. E-cloud build-up makes a steady-state difference between the bunches in the batch.

The threshold is determined by the highest brightness bunch in the beam, which is a far tail in the brightness distribution. This can be a reason for the poor reproducibility.

# “Damper Imperfections” ?

# “Damper Imperfections”?

1. **Digitizing of the damper's input and output?**

Those effects are very small to play any role for a short time of the squeeze. Otherwise, you will see a huge noise from the damper during hours of beam store.

2. **Imperfect phasing of pi/2?**

Beam stability is not too sensitive to this parameter, it could be from pi/4 to 3pi/4, and still the damper would do its job, only with somewhat lower efficiency. Since at the plateau we are not so sensitive to the gain, this imperfect phasing cannot be an issue.

3. **Some hardware/software failure**?

The damper was properly checked several times without any signature of its possible failure. It does not seem reasonable to suspect the damper suddenly fail at the end of the squeeze, and then suddenly recover.

# Without a big failure of the damper:

Coupled-bunch and beam-beam collective effects are excluded at the high-chroma & high-gain plateau.

Collective beam-beam adds ~30% (~70A) to the threshold octupole current, but incoherent beam-beam at the EoS subtracts 1.5-2 times more, ~ 100-140A.

# My MD Priority List

# My MD priority:

- Single bunch, single beam first, as several people stressed. LO threshold measurement at high chroma and high gain (higher priority) and zero gain (lower priority). Damping the beam after every measurement.

- 1*1 and 36*36 at the top, before and after the squeeze measurements at the plateau. Damper is on (higher priority) and off (lower priority)

- Do that for both polarities.

- At the cogging MD we did not see any effect from the tune separation, as it was predicted. However, no EoSI was once observed with higher tune separation (end of the Run). It makes it reasonable to check reproducibility of that.

# ICE Forum?

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- Web-based forums are powerful tools of communication we do not use yet. They are suited for the following important purposes:
  - Letting know signed people about new results and ideas in the theme.
  - Have public discussions, make arguments better expressed and open.
  - Help seeing the spectrum of ideas and their strength.

- What forum space is better to use? https://groups.google.com ?
- Forum structure?
- Anti-spam measures?

- Send me your suggestions.

- In any case I wish to start that ICE forum communication, inviting everybody to sign and post there, and see how it works.